THE RADIATION EFFECTS ON OPTICAL TRANSCEIVER SYSTEM OF SATELLITE ON BOARD AT NEAR EQUATORIAL LOW EARTH ORBIT

BY

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ABSTRACT

To improve performance and reduce the cost of the inter-satellite communication systems, academia and industry are active in discovering adequate solutions. Both satellite industry and communication start to work on a new paradigm in integrating the space, aerial, and terrestrial networks to form the three-dimensional of the 5G. Low Earth Orbit presents a niche for such projects. However, spacecraft, space stations, satellites, and astronauts are exposed to an increased level of radiation when in space, so it is crucial to evaluate the risks and performance effects associated with extended radiation exposures in missions and space travel in general. This thesis focuses on the LEO, especially in the near-equatorial radiation environment, and how the particles interact with materials in general and with inter-satellite optical wireless communication systems, in particular. The exposed dosage due to the LEO space environment radiation sources, as a function of orbital altitude, orbital inclination, and duration of the inter-satellite Optical Wireless Communication system under radiation, is investigated using existing empirical models. Radiation experiments supported with simulations have made it possible to obtain and evaluate the electron and neutron radiation impact on the optoelectronic components, namely the laser diode at the transmitter and the photodiodes at the receiver subsystems the optical link performance while onboard. Results have shown the degradation of the optoelectronics devices' performance under both radtions, which is affected the performance of the link at the system level. Results show as well the sensitivity of the transmitter subsystems compared to the receiver subsystem. The neutron radiation has been induced a system degradation up to 85% while the electron radiation up to 80%. This shows the importance of such an investigation to predict and take necessary and suitable reliable quality service for future space missions.

خلاصة البحث

تحسين الأداء وتقليل تكلفة أنظمة الاتصالات بين الأقمار الصناعية ، تنشط الأوساط الأكاديمية والصناعية في اكتشاف الحلول المناسبة. بدأت صناعة الأقمار الصناعية والاتصالات في العمل على نموذج جديد في دمج الشبكات الفضائية والجوية والأرضية لتشكيل ثلاثي الأبعاد لشبكة الجيل الخامس. يقدم Low Earth Orbit مكانًا مناسبًا لمثل هذه المشاريع. ومع ذلك ، تتعرض المركبات الفضائية والمحطات الفضائية والأقمار الصناعية ورواد الفضاء لمستوى متزايد من الإشعاع عندما تكون في الفضاء ، لذلك من المهم تقييم المخاطر وتأثيرات الأداء المرتبطة بالتعرض للإشعاع الممتد في البعثات والسفر الفضائي بشكل عام. تركز هذه الأطروحة على المدار الأرضي المنخفض خاصة في بيئة الإشعاع شبه الاستوائية وكيف تتفاعل الجزيئات الموجودة فيه مع المواد بشكل عام ومع أنظمة الاتصالات اللاسلكية الضوئية بين الأقمار الصناعية بشكل خاص. باستخدام النماذج التجريبية الحالية ، يتم فحص الجرعة المكشوفة بسبب مصادر إشعاع بيئة الفضاء المدار الأرضي المنخفض ، كدالة للارتفاع المداري ، والميل المداري ، والمدة التي يتعرض لها نظام الاتصالات اللاسلكية الضوئية بين الأقمار الصناعية تحت الإشعاع. أتاحت التجارب الإشعاعية المدعومة بالمحاكاة الحصول على وتقييم تأثير إشعاع الإلكترون والنيوترون على مكونات الإلكترونيات الضوئية مثل الصمام الثنائي لليزر في جهاز الإرسال والثنائيات الضوئية في الأنظمة الفرعية. و أظهرت النتائج تدهور أداء أجهزة الإلكترونيات الضوئية تحت كلا الإشعاعين ، مما أثر على أداء الارتباط على مستوى النظام. تظهر النتائج أيضًا حساسية أنظمة الإرسال الفرعية مقارنة بالنظام الفرعي لجهاز الاستقبال. تسبب الإشعاع النيوتروني في تدهور النظام بنسبة تصل إلى 85٪ بينما يصل إشعاع الإلكترون إلى 80٪. وهذا يوضح أهمية مثل هذا التحقيق للتنبؤ واتخاذ التدابير اللازمة والمناسبة لخدمة موثوقة الجودة المتاحة لبعثات الفضاء المستقبلية.

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Praise and Thanks due to almighty Allah, the lord, and the creator. His bounties on me are countless. This work would not be complete without his mercy, guidance, and support. May Allah SWT accept this humble contribution to Science and Knowledge from me and be counted in my good deeds.

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ISLAMIZATION

Islamic education is based on purification of the human personality, directing the intellect and its associated functions to reflect on this universe and reflect within oneself to arrive at the conclusion of the existence of the Creator, of His Uniqueness, Greatness, Power, and Care and Mercy to the humankind. This research work attempts to reflect upon that foundation. Space science has its origin in astronomy, the queen of the sciences. Muslims have enriched the science of astronomy. Historically, Ibrahim ibn Habib al-Fazari was the first Muslim scientist to be involved in pioneering work in astronomy. He predicted lunar and solar eclipses and worked on the lunar year, stars' movement, and the timing of prayers.
This knowledge led to a structured observation throughout the Muslim world. Many great Muslim astronomers, such as al-Khawarizmi, al-Battani, ibn Kathir, al-Sufi, al-Buzjani, ibn al-Haytham and al-Biruni benefited from Ibrahim ibn Habib al-Fazari's findings.

In the modern era, Muslim scientists space research should be strengthened to reflect the vision and inventiveness of our forefathers' Muslim scientists in enabling the Ummah to learn more about space and bargain for the benefits of space technology.

This research has attempted to contribute to scientific knowledge of space. The study has investigated the dynamic correlation and reaction of matters with space radiation.
The outcomes of the investigation demonstrated the effects of electron and neutron radiation on the performance degradation of laser diodes and photodiodes at the device and system levels. These findings will help better understand electron and neutron radiation effects on optoelectronic devices and systems in low-Earth orbit (LEO). As a result, these could be useful in increasing the quality performance of future inter-satellite optical wireless communication systems (IsOWC).

The systematic dynamic interaction of space environment and physical matters reported in this research work reveals one of Allah's attributes, *Al-Mubdi'*, the Producer, Originator, and Initiator of all. It is He who created the heavens and the earth, without a preceding prototype or model and with the greatest precision. That is the design of the Almighty, All-Knowing.

Thus, I believe that this research on space radiation and its effects on spacecraft communication strengthened the intellectual humankind's vicegerent on Earth, as it will contribute scientifically to the advancement and development of humankind's well-being on earth and beyond, albeit in a minor way. Allah says: "And you have not received knowledge except a little" Al-Isra (85).

I seek Allah's acceptance and sincerity.

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LIST OF ABBREVIATIONS

2-D	Two- dimensional
3-D	Three – dimensional
3 GPP	3rd Generation Partnership Project
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
dB	Decibel
EDRS	European Data Relay Satellite
OOK	On- Off Keying
GEO	Geosynchronous Orbit
GSM	Global System for Mobile Communication
IsOWC	Inter-satellite Optical Communication
ITU- R	International Telecommunication Union – Radio
IOT	Internet of things
LEO	Low Earth Orbit
LD	Laser Diode
MEO	Medium Earth Orbit
NeqO	Near Equatorial
LTE	Long Term Evolution
PD	Photodiode
PRBS	Pseudorandom Binary Sequence
QoS	Quality of Service
SATIN	Space- Aerial – Terrestrial Integrated Network

LIST OF SYMBOLS

D	diameter
d	distance
f	Frequency
λ	Wavelength
Q	Q factor
σ	Beat noise

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Inter-satellite Optical Wireless Communication (IsOWC) systems have the advantages of higher data transmission rate, less payload power requirement, and smaller terminal size and weight, which embodies IsOWC with promising features to meet the growing demands of future high-speed transmission with massive data in space (Li et al., 2018), (Liu, Zhao, Yang, et al., 2015). However, it is known that outer space is filled with high-energy particles, including protons, electrons, neutrons, and heavy ions. When these high-energy particles get incident onto optoelectronic devices, they will result in unavoidable damages to the material of devices, leading them ultimately into severe performance degradation and even malfunctioning (Seif El Nasr-Storey et al., 2013). For Malaysia, Near Equatorial Low earth orbit (abbreviated in short as "NEqO") is a niche orbit where a higher revisit of satellites (16 times a day), is achieved as compared to sending the satellite to other orbits(Suparta & Zulkeple, 2018). In 2010, Malaysia launched its satellite, Razak Sat 1 to Near Equatorial Low Earth Orbit, equipped with a high-resolution camera intended for application to land management, resource development, and forestry. Unfortunately, the satellite stopped communicating with the base station on earth after one year. It is believed that it was affected by radiation, thus impairing its devices' communication features as stated in (Suparta & Zulkeple, 2017). This is encouraging to investigate the radiation effects on the main devices deployed in satellites at Near Equatorial Low Earth Orbit for future space missions in that dynamic orbit (Ya'acob et al., 2017).

Similar projects have been planned to be launched into LEO soon to improve performance and reduce the cost of the communication systems; academia and industry are active in discovering adequate solutions (Zhang et al., 2020a). With the introduction of the fifth-generation, 5G, both the satellite industry and communication start to work on this new paradigm to integrate the space, aerial, and terrestrial networks to form the three-dimensional 5G. Some infrastructures already existed in this latest move, such as the iridium with its 66 active satellites constellation in providing voice and low data service for cellular phones. In recent years, some space missions have been launched and Global Express to provide more advanced communications services with high throughput satellites (HTS). The Geosynchronous Earth Orbit (GEO) system has been the most popular approach in providing commercial satellite communication services; however, the propagation delay, attenuation, and higher launching cost make LEO systems a better choice. The Telesat and On web constellation further prove the candidacy of LEO, besides its short propagation, global coverage, and low launch cost (Popescu, 2017).

Recently, some initiatives have been taken to enhance the 5G network to integrate it with non-terrestrial access technology, such as the 3 GPP- R16 plan (Networks, 2014). It has been believed that this integration will play an essential role in physical attacks and natural disasters, where it will assure reliability, flexibility, and large an efficient broadcast. Furthermore, the space-aerial-terrestrial integrated networks (SATIN), will support the internet of things initiative, where the existing terrestrial 5G networks need to handle a massive amount of data generated by internet of things (IoT) devices and provide connectivity to billions of devices with varying degree of Quality of service (QoS). However, it is believed that space radiation would

present a threat in the long term to the mission's performance (Liu et al., 2016). Wireless optical communication offers one of the best choices in inter-satellite communication systems. The technology of inter-satellite optical wireless communication systems (IsOWC) is known for its efficiency over the RF communications systems. However, it is believed that the space radiation environment may jeopardize the performance of such a system in the long term(Liu, Zhao, Yang, et al., 2015). Therefore, this research will investigate the electron and neutron radiation effect on optical wireless communication at the devices and system level.

1.2 PROBLEM STATEMENT

Physics and device simulations study have always been viable alternatives for space exploration as it is difficult, hazardous, and costly to emulate high-energy space particles in the lab. Studies of radiation hard electronics related to space missions in general and at Near Equatorial low earth orbit are few. It has been believed that optoelectronic devices implemented in inter-satellite optical wireless communication (IsOWC) system terminals may be exposed to the complex space radiation environment for years, and can cause serious degradation of the system performance and lead to its failure (Liu, Zhao, Zhao, Li, Dong, et al., 2017). Subsequently, the performance of the communication system will be influenced, and the reliability of communication is at risk. The previous study has mainly done on gamma radiation for the characterization of the transceiver and extending it to the whole optical link system (Li et al., 2018). At the same time, others have done partially i.e. only the characterization of the transceiver devices with neutron radiation (Lischka et al., 1995), proton radiation(Jiménez et al., 2006), and gamma radiation (Seif El Nasr-Storey et al., 2013), without testing on the system level.

This proposed research is unique in which it combines the characterization of the transmitter (laser) and receiver (photodetector) before and after electron and neutron radiation doses of the range of the intended orbit, Near Equatorial Orbit (NEqO), where the study will be extended to simulation and modeling of the Inter-satellite Optical Wireless Communication system at NEqO.

1.3 RESEARCH OBJECTIVES

This research aims to study the electron and neutron radiation on IsOWC system at Low earth orbit, especially at NEqO; the detailed objectives are:

1- To characterize the electrical and optical performance parameters of the IsOWC transceiver before radiation.

2- To investigate experimentally and characterize the performance degradation of the IsOWC transceiver under electron and neutron radiation at low earth orbit.

3- To model the performance degradation of the IsOWC transceiver under electron and neutron radiation, with different wavelengths and modulation techniques at NEqO.

1.4 RESEARCH PHILOSOPHY

This research aims to investigate the radiation environment at low earth orbit, in particular at the Near Equatorial (NEqO); the study will focus on the electron and neutron radiation effect on space crafts that operate in this newly exploited orbit. The investigation will converge more on the impact of the above particles on the optical satellite communication systems. Thus, after completing this research, it is believed it

will help quantify the radiation and proposed a model that describes the radiation environment portfolio of this dynamic orbit. Thus, suitable radiation hardness methods may be recommended for future works and implemented to maximize the IsOWC link quality performance.

1.5 RESEARCH METHODOLOGY

The methodology used in this research follows four main steps: a literature review of technical and scientific papers on the radiative environment low earth orbit in general and at NEqO in particular. An assessment of the radiation effect on the optoelectronic devices of electron and neutron radiation based on previous related studies has been carried out. Then, the selection of the commercial-off-the-shelf (COTS) optoelectronics devices, namely the laser in the transmitter and the photodiodes in the receiver, and radiate them with the electron and neutron radiation accordingly. The degradation of the devices will be incorporated in a well-designed optical satellite communication link in OptiSystem, where the Analytical modeling of the system performance degradation under the electron and neutron radiation at NeqO can be derived.